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Rocket Observations of Solar Protons during the November 1960 Events, 2

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Abstract. Rocket observations of solar protons made from Fort Churchill during the November 15, 1960, event are described. Four spectra showing a flattening toward the threshold energy of 4.0 Mev and a rise at even lower energies are given. The decay of intensity was observed to be proportional to $1/T^3$ above an energy of 100 Mev. A plot of the riometer observation against the integral intensity of solar protons above 10 and 100 Mev for eight rocket shots is given. Information concerning the presence of a large intensity of α particles about 2000 UT on November 16 is presented, and the general interpretation of the November 15 event is discussed.

Introduction. This paper continues the analysis of the rocket observations of solar protons made during November 1960 at Fort Churchill. In part 1 [*Ogilvie, Bryant, and Davis,* 1962] we discussed the results of rocket shots during the November 12 event; here we describe the four rocket shots during the November 15 event. Nike-Cajun rockets were fired during these events to an altitude of about 130 km, each carrying two scintillation counters and a Geiger counter. A nuclear emulsion package was also carried, and some results of this work are displayed here for comparison with our counter measurements. They will be described fully by Fichtel and Guss. The details of the apparatus and method of analysis have already been described [*Davis, Fichtel, Guss, and Ogilvie,* 1961; *Ogilvie, Bryant, and Davis,* 1962], and we shall not repeat them here, since there is no difference in the method of treatment.

On November 15 at 0207 UT there was a 3^+ flare lasting more than 2 hours and originating in solar region 5925, then situated at coordinates 32°W 30°N. A neutron monitor increase with a short rise time started at 0230 UT, and reached, for instance at Deep River, an amplitude 75 per cent above normal at 0242 UT [*Steljes, Carmichael, and McCracken,* 1961].

The November 15 solar proton event differed from that of November 12 because of the very rapid rise in the neutron-monitor rate. This has been interpreted by Steljes, Carmichael, and McCracken as a consequence of the presence of a fairly well-ordered system of magnetic fields connecting the earth to the sun at the time of the flare, since the earth was then inside the trapping region associated with the November 12 event. The well-ordered field system is considered to supply a path for the rapid passage of solar particles between the sun and the earth. Well-marked fluctuations and anisotropies detected by means of the network of neutron monitors occurred immediately after the initial rise [*McCracken,* 1962*a, b, c*]; but these cannot be studied by us. All the rocket shots described here occurred after isotropy had been established and was presumably continuing.

Results. No rockets were fired during the early part of the event, but the subsequent decrease in intensity of solar protons was followed between 40 and 95 hours after the flare by means of four rockets shot at the times given in Table 1.

In Figure 1 we see the spectra found during the later part of this event, showing, as in part 1, some intensity values determined by Fichtel and Guss from completely independent emulsion measurements using the same rockets. The points on these integral spectra below 1 Mev were obtained from the results of the ZnS scintillator.

The results from the CsI counter are analyzed to provide the best fit to a power-law spectrum above an energy of 1.8 Mev. It was necessary in spectra considered in this paper to introduce a cutoff at an energy of a few Mev, and this

TABLE 1

Rocket	Time, UT	Time after Flare	Emulsion Recovery	Decibels Absorbed at 30 Mev
1013	1951, Nov. 16	41h 46m	Yes	5.6
1014	0600, Nov. 17	51h 53m	Yes	1.4 (night)
1026	0339, Nov. 18	73h 32m	Yes	1.1 (night)
1027	2139, Nov. 18	91h 32m	No	2.3

cutoff presumably represents the geomagnetic threshold at the time. After magnetic activity had ended, the cutoffs required to fit the results from rockets 1026 and 1027 are both 4.0 Mev, to be compared with the predicted value of 5.8 Mev. The limits shown on the slope of the line for rocket 1013 are generally typical of all. The highest energy Geiger-counter point is derived from air absorption during the ascent of the rocket.

Observations exist of the flux of protons with energy greater than 30 Mev found by counters carried on Explorer VII [*Lin*, 1961]. Table 2 shows how our results at Fort Churchill compare with the satellite observations closest in time to the firing of the rocket.

The spectra are of the same curved shape that characterized those found during the September 3, 1960 [*Davis, Fichtel, Guss, and Ogilvie*, 1961], and November 12, 1960 (part 1), events, but they do not show a marked progressive steepening toward higher energies as the time from the flare increases. The groups of very low-energy particles detected on November 12 and 13 occur again in these spectra, with gradually decreasing intensity. In part 1 it was suggested that these are probably not part of the spectrum of particles accelerated at the flare, but that at least a large proportion of them are associated with the plasma in the earth-sun region. This interpretation of the low-energy particle group as a separate phenomenon is consistent with the results of *Davis, Berg, and Meredith* [1960] and [*McDiarmid, Rose, and Budzinski*, 1961], who found intensities of the order of 10^3/cm^2/sec/ster of protons

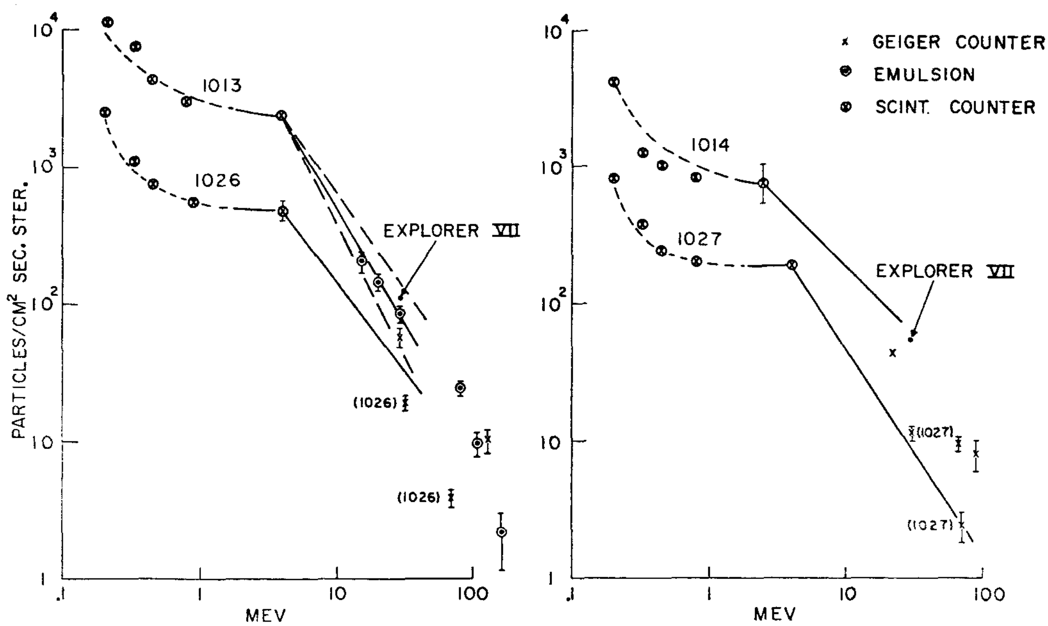

Fig. 1. Spectra of solar protons for the four rocket shots discussed.

TABLE 2

Rocket Data				Explorer VII Data				
						Geographic		
Rocket	Intensity Scintillation Counter	30 Mev Geiger Counter	Time	Flux	Time	Latitude	Longitude	Altitude, Km
1013	84 ± 20	56 ± 2	1951	100	2337	47.3	73.2	843
1014	60 ± 20	30 ± 5	0600	23.5	0304	50.4	103.3	912
1026	36 ± 10	20 ± 2	0339	10	0239	50.2	105.2	889
1027	9 ± 3	11 ± 1	2139	6.1	0039	49.9	81.3	866

of 100–800 kev energy in rocket shots not penetrating visible auroras, but during periods of auroral activity, fired from Fort Churchill. During the time of these rocket shots the intensity of particles with energy greater than 2 Mev was essentially zero, there being at that time no solar-proton event. By 75 hours after the flare on November 15, fluctuations in the geomagnetic field had reduced to normal. The intensity between 0.2 and 2 Mev, here called ΔJ, was then of the order of 10^3/cm^2/sec/ster.

We show in Figure 2 the time variation of the intensity of particles with energy greater than 10 Mev and greater than 100 Mev plotted against time from the flare. These quantities decay with time in a generally similar way, and the intensity greater than 100 Mev presents a better fit to a straight line on a log-log than on an exponential graph, the slope being −2.9. In their paper on the July 16, 1959, event *Anderson and Enemark* [1960] report a similar rate of decrease of the intensity of particles at balloon altitudes (about 6 g/cm^2) at Resolute, which is within the polar cap, and a similar constancy of spectral exponent. The event in July 1959 also occurred a short time after a large event, and so we might expect that in this instance also a relatively easy path existed joining the sun to the earth. The rate of decay of solar protons has often been observed [*Arnoldy, Hoffman, and Winckler*, 1960] to be slower than T^{-3}, and in fact many events appear to follow a T^{-2} law. Thus it appears that the state of the interplanetary medium connecting the earth and sun has a profound effect upon the trapping and propagation of solar particles. The $1/T^3$ dependence characteristic of expansion of a trapping region in three dimensions appears to correspond to the simplest case, when the earth is situated inside it.

Figure 3 shows the observed intensity of particles with energy greater than 10 and 100 Mev plotted against riometer absorption in decibels for all the rocket observations we have made. The two lines, which assume absorption proportional to the square root of intensity, are fitted to the points by inspection. This would be the case for the theoretical calculations that have been made, and the measured points lie close to the line but separated from it by more than the

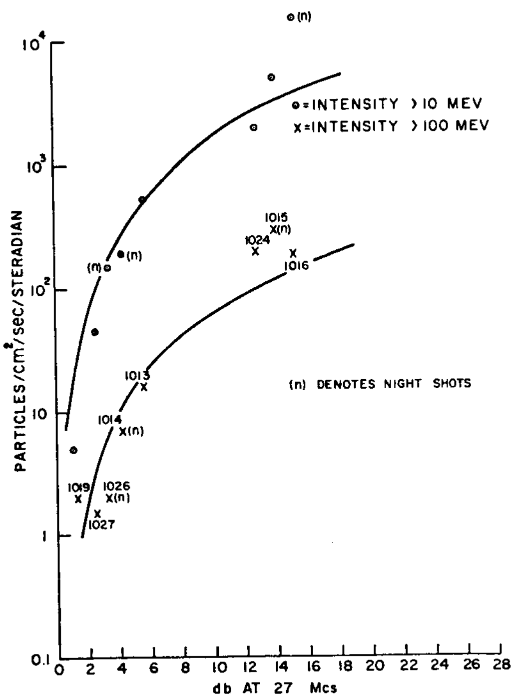

Fig. 2. The observed intensity of particles with energy greater than 10 Mev and greater than 100 Mev, plotted against 27 Mc/s riometer absorption. The two lines, fitted by inspection, assume absorption proportional to the square root of the intensity.

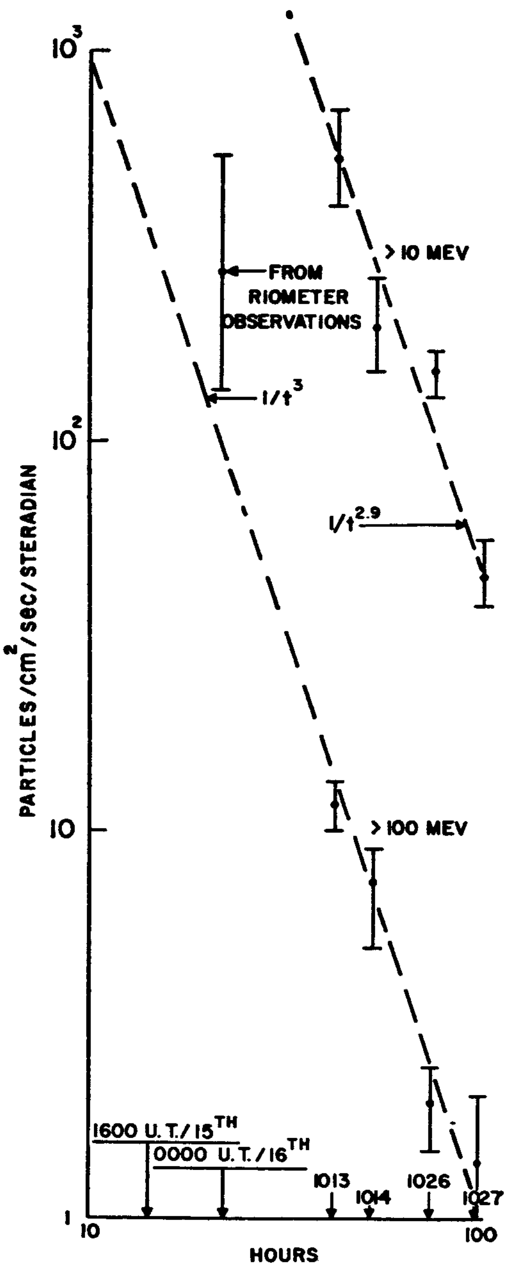

Fig. 3. Time variation of integral intensity of protons above 10 Mev and above 100 Mev. The zero of time is taken as the time of the flare.

errors of measurement at large intensities. The reduction to daylight conditions has been carried out using a ratio 3:1 found by *Reid* [1961] in his theoretical treatment of solar proton bombardment of the atmosphere. The experimental values of day-to-night ratio, which fall in the range 3–4, are subject to systematic error due to decay of the incident protons intensity.

Between about 1600 UT on November 15 and 0000 UT on November 16 the riometer was off scale, >15 db, at Fort Churchill. We thus deduce an intensity in excess of 270/cm²/sec/ster for energies greater than 100 Mev between the times marked on Figure 2, which is further evidence that the decay law has an exponent greater than or equal to 3.

Theoretical calculations of the absorption due to protons incident upon the atmosphere have been made by *Reid* [1961] and *Brown and Weir* [1961]. Both predict that the electron-density profile, and in particular the position of its peak at about 80 km above the earth, is extremely insensitive to the form of the incident proton spectrum. Reid, for instance, assumes a differential spectrum of the form

$$N(E)\,dE = A/E^5\,dE \quad \text{with} \quad A = 2.24 \times 10^5$$

This spectrum is arbitrarily cut off below 40 Mev, and the protons are incident isotropically. The insensitivity of the electron-density profile to the spectrum is due to the fact that most of the protons pass through the important region where absorption is a maximum considerably before reaching the end of their range. To a first approximation, and assuming that not very many protons stop in this region because of a low incident energy or an oblique incident direction, the absorption depends upon the number of incident protons. The spectrum enters into the absorption principally by fixing the number of particles between a given energy and the cutoff.

This cutoff for our measurements is about 4 Mev, and the spectral slopes fall in the range 1.5 to 3.0. For this spectral range our curve thus allows a prediction to be made of the absorption that will be given by a flux of protons having a certain intensity above 10 Mev or above 100

TABLE 3. NASA 1013, 1951, Nov. 16, 1961

Detector	Energy Interval for Particles, Mev	α Particle Intensity per cm²/sec/ster
CsI	12 to 70	230 ± 50
ZnS	2.2 to 10	500 ± 75

Mev, where the spectrum continues back to 4 Mev. It is not possible to make a close comparison with the calculations, owing to the differences in the cutoff. In view of the uncertainty in the atmospheric parameters that must be inserted in the calculation, it would be interesting to see the results of recalculations made to fit our spectra as closely as possible.

The steep region of the upper curve in Figure 3 for intensities less than about $10/\text{cm}^2/\text{sec}/\text{ster}$ shows that the riometer is quite insensitive to low intensities of particles. We would expect that small solar events might occur and not be detected, even though the intensity at energies of the order of 10 Mev is many times cosmic-ray background. Satellite observations at an energy of about 10 Mev are required to show up such increases.

These observations support the contention that the earth was inside a large trapping region, originally connected to the sun by a system of direct field lines and expanding freely, without appreciable diffusion of particles of these energies from the expanding end. A diffusing barrier has two main effects upon trapped particles: it causes the spectrum to steepen with time, owing to the preferential loss of high energies; and reflection from the barrier holds up the intensity inside the region at late times. This is illustrated clearly in the analysis of the February 23, 1956, event [*Meyer, Parker, and Simpson*, 1957].

Both scintillation-counter instruments in all the rockets flown into the November 12 and 15 events incorporated an energy-sensitivity level that was too high to respond to protons entering the counter through the nominal solid angle. This was intended to detect α particles, but there was a small background due to protons entering through the wall of the rocket and traversing the crystal obliquely. This background has been calculated for the CsI counter as a function of the observed spectral exponent and cutoff, and it has been compared with the observed rate. The ZnS counter was sensitive to α particles in the energy range 2.2 to 10 Mev, and the CsI counter to α particles in the energy range 12 to 70 Mev. The observed rates are consistent with there being no significant contribution due to α particles for all shots except 1013, the first rocket flown in the November 15 event. By this we mean that the observed rate is within two standard deviations of the calculated background for the CsI counter.

The observed rate for rocket 1013 was three times the calculated background for the CsI counter, which differs from it by four standard deviations. For the ZnS detector it was ten times the background observed in other shots. The corresponding α-particle intensities are set out in Table 3. This represents about one α particle to four protons in the same energy per nucleon interval. The particle spectrum is flatter than the proton spectrum in this energy range.

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